Adaptive Control Strategy in Electromagnetic Levitation System

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Abstract – This paper deals with control system design strategy for electrolmagnetic suspension (E.M.S.) system. For a successful control of E.M.S. system, the nature of E.M.S. system is deeply studied in the view point of non-linear, open-loop unstable, time-varying, non-minimum phase system. To find a special control treatment for E.M.S. system, analyses and simulations for various models are carried out. As one of the successful candidates, adaptive control concept is introduced and sample hardware system using digital signal processor is implemented.

1. Introduction

To adopt or not an electromagnetic levitation technology for a new transportation system for the coming century is currently becomming a hot issue in Korea. There are two kinds of diffenrent structure in using electromagnetic levitation technology for transportation system; one is electromagnetic suspension (E.M.S.) system using linear indution motor (L.I.M.) for propulsion, the other is electrodynamic suspension (E.D.S.) system using linear synchronous motor (L.S.M.) for propulsion. In this paper, a basic feature of simple E.M.S. system is analyzed. Considered model is a single magnet levitation system. As shown in the following section, this model is non-linear, open-loop unstable and time-varying. Furthermore discrete version of the model becomes a non-minimum phase system.

The above 4 words (non-linear, open-loop unstable, time- varying and non-minimum phase) are enough to say that a E.M.S. system is a theoretically very difficult system to be controlled well.

The purpose of this work is to introduce an adaptive control concept for a successful control of E.M.S. system. A short introduction to single magnet levitation system modelling is made in section 2. Classical concept control design and simulation result is described in section 3. As a constant gain simple feedback controller is not enough for the system, the need of using a time-varying gain feedback control concept is introduced in section 4. Another approach to save this problem may be non-linear and robust control design. but in this work, only adaptive concept is roughly analyzed. A short comment and sample hardware implementation using digital signal processor (D.S.P.) is made in section 5.

2. Problem statement

In this section, the modelling and control problem of E.M.S. system [Sinha, 1987] are simply described.

The attractive force in E.M.S. system is proportional to square of magnet current and inverse proportional to square of airgap between a rail and a suspended magnet. Because of the above characteristic, E.M.S. system is non-linear and open-loop unstable. Also in terms of the fact that the instantaneous magnet inductance is the function of magnet current and airgap, it becomes a time-varying system.

To analyze E.M.S. system, a linearized model is necessary. Referring to Sinha's work, the linearized state space model of open-loop system is as follows:

$$
\begin{bmatrix} \Delta \dot{z}(t) \\ \Delta \ddot{z}(t) \\ \Delta \dot{i}(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ \dfrac{K_z}{m} & 0 & -\dfrac{K_i}{m} \\ 0 & \dfrac{K_z}{K_i} & -\dfrac{R}{L_o} \end{bmatrix} \begin{bmatrix} \Delta z(t) \\ \Delta \dot{z}(t) \\ \Delta i(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \dfrac{1}{L_o} \end{bmatrix} \Delta v(t) \qquad (2.1)
$$

where $\Delta z(t)$, $\Delta \dot{z}(t)$, $\Delta i(t)$: state variables
  m : the mass of suspended magnet
  R : the resistance of magnet
  L_o : the inductance of magnet winding
        at equilibrium point (i_o, z_o)
  K_i, K_z are defined as follows

$$
K_i = \left. \frac{\partial F(i,z)}{\partial i} \right|_{(i_o,\, z_o)} \qquad K_z = \left. \frac{\partial F(i,z)}{\partial z} \right|_{(i_o,\, z_o)}
$$

$\Delta v(t)$: the voltage applied to magnet

The linearized open-loop transfer function is

$$
\Delta Z(s) = \left[-\frac{K_i/mR}{\dfrac{L_o}{R} s^3 + s^2 - \dfrac{K_z}{m}} \right] \Delta V(s) \qquad (2.2)
$$

which has relative degree 3.

The above transfer function shows that for a given mass, K_i controls the input-output gain of the open-loop system while K_z controls its poles. Therefore the variations of K_i and K_z effect on the stability of closed loop system. Also its relative degree is 3, it may become non-minimum phase system with the small sampling time in digital control. Also the transfer function indicates that E.M.S. system is unstable in open loop owing to the pole on the right-half s-plane and feedback of at least position (airgap) is necessary to achive stability.

E.M.S. system can be drived by either voltage source chopper or current source chopper. In this paper, current source type, is mainly considered.

The airgap to current transfer function becomes

$$
\frac{\Delta Z(s)}{\Delta I(s)} = \frac{-K_i/m}{s^2 - K_z/m} \qquad (2.3)
$$

The degree of this transfer function is 2. Practically the time delay caused by R-L circuit becomes one of the

important control problems. Since the magnet current is determined by control circuit, fast response can be obtained practically in digital control.

Thus E.M.S. system has three control problems as follows:

- non-linear
- open-loop unstable
- time-varying
- 3 of reletive degree

3. Non-Adaptive control

3.1 Linear model simulation

In section 3.1, the state feedback control of current source linearized model is shown. The linearized model is approximately made around the equilibrium point. The linearized model is useful in the analysis of control system. But if there is large perturbation in practical system, the environment around the equilibrium point becomes different. From this fact, the non-linear model is necessary to simulate well the practical system.

The current source state equation is written below.

$$\begin{bmatrix} \Delta \dot{z}(t) \\ \Delta \ddot{z}(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -K_z/m & 0 \end{bmatrix} \begin{bmatrix} \Delta z(t) \\ \Delta \dot{z}(t) \end{bmatrix} + \begin{bmatrix} 0 \\ -K_i/m \end{bmatrix} \Delta i(t)$$
(3.1)

The simulation parameters used are presented.

$K_i = 221$ [N/A]
$K_z = 44233.6$ [N/M]
$m = 8.5$ [kg]
$K_g = 800$ [A/M]
$K_v = 20$ [A/M/sec]
$i_o = 0.8$ [A]
$z_o = 4$ [mm]
initial airgap error $\Delta z(0) = 6$ [mm]
input constraint: maximum current is 10 [A].
state constraint: maximum airgap perturbation = 10 [mm]
minimum airgap perturbation = -4 [mm]

In practice, there are strong constraints in E.M.S. system. The stability of the closed-loop system is dependent on these input and state constraints. So the stable controller for the system with some constraint is necessary [Tsang and Clarke, 1988].

The simulation result is shown in Fig. 3.1. To analyze the closed loop control system, root locus is used.
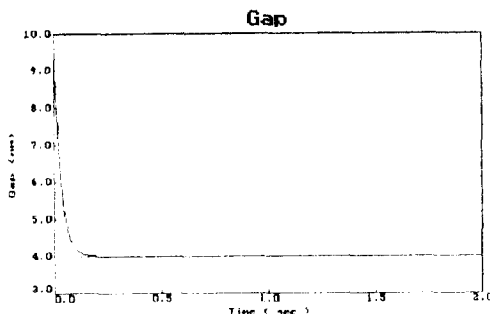

Fig. 3.1 Linearized model simulation

The closed loop characteristic equation is

$$m s^2 + K_v K_i s + K_g K_i - K_z = 0$$
(3.2)

and the closed loop poles are located at

$$s = -488.3216, -31.96373$$

so it is stable.

The open-loop transfer function with K_g is

$$\frac{K_g K_i}{m s^2 + K_v K_i s - K_z}$$
(3.3)

Root locus of MagLev system with gain K_g is shown in Fig. 3.2. In this case, K_v is set to 20.
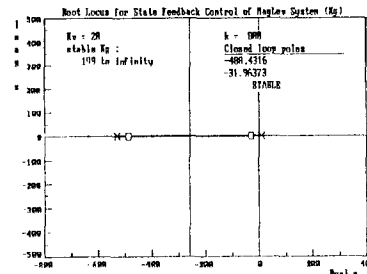

Fig. 3.2 Root locus of MagLev system with gain K_g

The open-loop poles are located at s ≈ -530.2097, 9.814 so it becomes unstable. The stable region of this system with K_g is 199.991 to infinity theoritically. Fig.2.2 shows that if K_g is large than 199.991, the closed loop system is always stable. But in practice, the maximum value of K_g is surely finite.

Also root locus of MagLev system with gain K_v is shown in Fig. 3.3. In this case, K_g is set to 800.

The open-loop transfer function with K_v is

$$\frac{K_v K_i s}{m s^2 + K_g K_i - K_z}$$
(3.4)

If $K_g K_i$ is larger than K_z, the open-loop poles always are located on imaginay axis of s plane. Therefore the closed loop system is stable at all times. Inversely if $K_g K_i$ is smaller than K_z, one of the open-loop poles always is located on positive real axis of s plane. Because of open-loop zero at the origin, the close-loop system always is unstable.
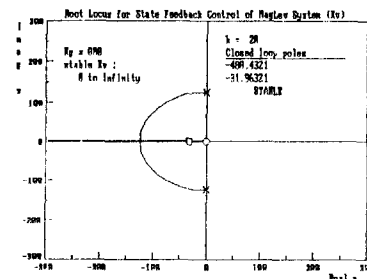

Fig. 3.3 Root locus of MagLev system with gain K_v

3.2 Non-linear model simulation

In this section, the simulation of non-linear model is carried out. The voltage source non-linear state equation is written in eq. (3.5).

$$\begin{bmatrix} \dot{z}(t) \\ \ddot{z}(t) \\ \dot{i}(t) \end{bmatrix} = \begin{bmatrix} \dot{z}(t) \\ -\dfrac{\mu_0 N^2 A}{4m}\left[\dfrac{i(t)}{z(t)}\right]^2 + g \\ \dfrac{i(t)}{z(t)}\dot{z}(t) - \dfrac{2Rz(t)i(i)}{\mu_0 N^2 A} + \dfrac{2z(t)}{\mu_0 N^2 A}v(t) \end{bmatrix} \quad (3.5)$$

The current source state equation is given in eq. (3.6).

Differently from the linearized equation, the non-linear model has singularity of airgap. So new constraint must be given to the non-linear model to avoid singularity.

$$\begin{bmatrix} \dot{z}(t) \\ \ddot{z}(t) \end{bmatrix} = \begin{bmatrix} \dot{z}(t) \\ -\dfrac{\mu_0 N^2 A}{4m}\left[\dfrac{i(t)}{z(t)}\right]^2 + g \end{bmatrix} \quad (3.6)$$

The acceleration signal $\ddot{z}(t)$ is dependent on the gravitational acceleration, magnet current and airgap signal. If the acceleration of the suspended magnet is zero, then the magnet current and airgap signal become the equilibrium point (i_0, z_0).

The 4th order Runge-Kutta algorithm is used to integate the non-linear system. The integration step size of Runge-Kutta algorithm is 1 [msec]. The simulation parameters used are presented as follows.

$$\mu_0 = 4\pi \times 10^{-7}$$
$$K_i = 221 \text{ [N/A]}$$
$$K_z = 44233.6 \text{ [N/M]}$$
$$m = 8.5 \text{ [Kg]}$$
$$K_g = 800 \text{ [A/M]}$$
$$K_v = 20 \text{ [A/M/sec]}$$
$$i_0 = 0.8 \text{ [A]}$$
$$z_0 = 4 \text{ [mm]}$$
$$z(0) = 10 \text{ [mm]}$$

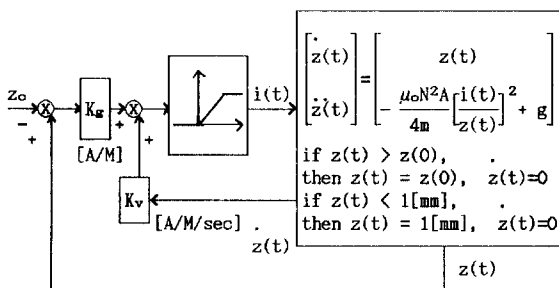The total block diagram of control system is shown in Fig. 3.4.

Fig.3.4 State feedback control of non-linear model

① mass change

Initial mass of E.M.S. system is 8.5 [Kg]. At 1 [sec], mass is changed to 20 [Kg]. This means the parameter variation of non-linear system. Hence it needs the

adequate variation of control parameter. In practice, the magnitude of mass change is at most 20 percent of total weight of suspended vehicle. However in this simulation, very large quantity varyies varied in order to assess the suspension stiffness. The simulation result is shown in Fig. 3.5.
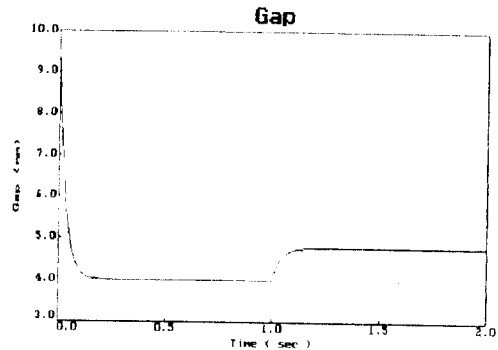

Fig.3.5 Non-adaptive control when mass changes

As a result of simulation, it is found that state feedback control gives good transient response, i.e. small rising time. As shown in section 3.1, the adequate feedback gains K_g, K_v give stable response. But when mass increases, large steady state error is generated. This fact means that the fixed gain feedback controller is not proper to time-varying system. In the E.M.S. system, stiffness may be increased by increasing the loop gain. But in this method, there is an upper limit due to high gains.

Another method is to adjust the nominal current. This reduces the steady state error but it has the problem of the gain to be adjusted automatically.

② airgap change

Initial input is 4 [mm]. At 1 [sec], it is changed to 4.5 [mm]. Airgap change means that the variation of the operating point of non-linear E.M.S. system. Of course, this alters the system parameters K_i, K_z, L_0. Simulation result is given in Fig. 3.6.
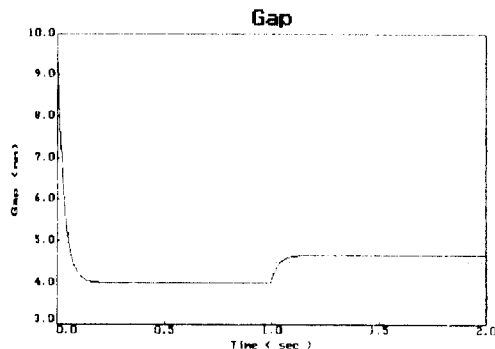

Fig. 3.6 Non-adaptive control when airgap changes

As shown in Fig. 3.6, when the reference airgap is varied, output airgap signal follows the input with small steady state error. In experiments, if the loop gain is very large to increase stiffness, the closed loop system becomes unstable, i.e. the magnet runs against the rail, due to the non-linearity. This is shown in section 3.3.

3.3 Experimental results for a single magnet

In this section, experimental device is briefly described. KD2300-8C made in Kaman, USA, which uses eddy current, is used to measure airgap between the rail and the magnet. 3165A-5G made in Dytran, USA, is used to measure the acceleration of suspended vehicle. In experiments, D.C. source voltage is 50 [V]. The peak-to-peak voltage of saw-tooth wave in chopper circuit is 12 [V]. Experimental result when gap changes is in shown Fig. 3.7.
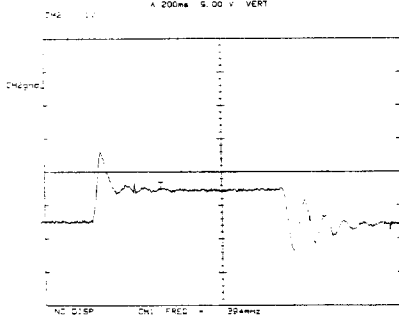

Fig.3.7　Experimental result when input varies with state feedback control

It is shown that because of non-linear characteristic in E.M.S.system, large overshoot and oscillation is made. Of course, this bad result would be decreased if feedback gain decreases. Design of suitable band-pass filter is not dealt with in this paper.

4. Adaptive control of E.M.S. system

4.1 review for adaptive control

Adaptive control is used to control the time-varying or unknown system by adjusting the controller parameter. Although slow processes like chemical reactor were main applications for adaptive control technology, recent progress in micro-computer and computing devices like D.S.P. chips has enlarged the application fields of adaptive technology.

In 1973, Astrom showed Minimum Variance Control(MVC). Subsequently Generalized Minimum Variance Control(GMVC) was proposed by Clarke and Gawthrop [1975]. Also Adaptive Pole Assignment Control(APAC) and Generalized Predicitve Control(GPC) was proposed　by Goodwin[1984], Clarke [1987]. GPC algorithm is very robust but has very large computational load. Especially, Model Reference Adaptive Control and MVC cannot be used for non-minimum phase system. Also GMV can be applied for non-minimum phase system only to a limited range.

In this paper, Adaptive Pole Assignment Control that can be applied to non-minimum phase system is used. The current source type is chosen as simulation model and the 4th order runge kutta method is picked up as integration algorithm of non-linear E.M.S. system. With sampling period T_s, the recursive least square algorithm with exponetially data weighting identifies the parameter of sampled E.M.S. system.

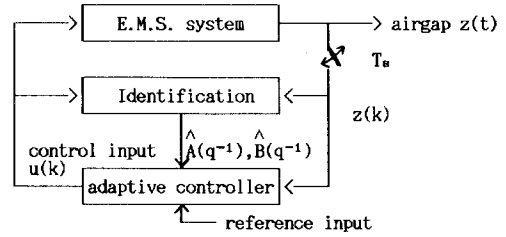The total block diagram of adaptive control system is shown in Fig. 4.1.

Fig.4.1　Adaptive control of E.M.S. system

Sampled plant model is presented as follows

$$y(k) = -a_1 y(k-1) -a_2 y(k-2) + b_0 u(k-1) + b_1 u(k-2) \quad (4.1)$$

The data vector $\phi^T(k-1)$ and parameter vector θ^T are set as follows

$$\phi^T(k-1) = [-y(k-1) \ -y(k-2) \ u(k-1) \ u(k-2)]$$

$$\theta^T = [a_1 \ a_2 \ b_0 \ b_1] \quad (4.2)$$

the above representations is denoted by regressor form

$$y(k) = \phi^T(k-1) \ \theta \quad (4.3)$$

In this way R.L.S.E. with exponentially data weighting used in this paper is presented.

$$\hat{\theta}(k) = \hat{\theta}(k-1) + \frac{P(k-2)\phi(k-1) \ [y(k) - \phi(k-1)^T\hat{\theta}(k-1)]}{\alpha(k) + \phi(k-1)^TP(k-2)\phi(k-1)} \quad (4.4)$$

$$P(k-1) = \frac{1}{\alpha(k)} \left[P(k-2) - \frac{P(k-2)\phi(k-1)\phi(k-1)^TP(k-2)}{\alpha(k) + \phi(k-1)^TP(k-2)\phi(k-1)} \right] \quad (4.5)$$

$$\alpha(k) = \alpha(k-1)\alpha_0 + (1 - \alpha_0), \quad \alpha(0) = 0.95, \quad \alpha_0 = 0.99 \quad (4.6)$$

We define polynomials $A(q^{-1})$, $B(q^{-1})$ as eq.(4.7)

$$A(q^{-1}) = 1 + a_1q^{-1} + a_1q^{-2}$$

$$B(q^{-1}) = q^{-1}(b_0 + b_1q^{-1}) \quad (4.7)$$

and diophatine equation is presented　below

$$A(q^{-1}) \ L(q^{-1}) + B(q^{-1}) \ P(q^{-1}) = A^*(q^{-1}) \quad (4.8)$$

where　$L(q^{-1}) = l_0 + l_1 \ q^{-1}$, $\quad$ (4.9)
$\quad P(q^{-1}) = p_0 + p_1 \ q^{-1}$
$\quad A^*(q^{-1}) = a_0^* + a_1^*q^{-1} + a_2^*q^{-2} + a_3^*q^{-3}$ (4.10)
$\quad A^*(q^{-1})$ is desired closed loop-pole polynomial.

The coefficients of controller polynomial $L(q^{-1})$, $P(q^{-1})$ are obtained by eq.(4.11)

$$\begin{bmatrix} l_0 \\ l_1 \\ p_0 \\ p_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ a_1 & 1 & b_0 & 0 \\ a_2 & a_1 & b_1 & b_0 \\ 0 & a_2 & 0 & b_1 \end{bmatrix}^{-1} \begin{bmatrix} a_0^* \\ a_1^* \\ a_2^* \\ a_3^* \end{bmatrix} \quad (4.11)$$

Control input u(t) is determined by eq.(4.12)

$$L(q^{-1}) \ u(k) = P(q^{-1}) \ [y(k) - y^*(k+1)] \quad (4.12)$$

where　$y^*(k+1)$ is desired output at time instant (k+1).

4.2 Simulation results

In section 4.2, simulation results of pole-assignment control for E.M.S. system is presented. As non-adaptive control, performance of adaptive PAC is shown by two way. Since E.M.S. system is fast time-varying, we must consider convergence ability of L.S. algorithm to real plant parameters. Choice of initial parameters has another practical importance. Sampling period is 2 [msec].

① mass change

Mass change means load disturbance and parameter variation of E.M.S.system. If the variation is very large it is required to adjust the controller parameter to get good control performance, i.e. stiffness. Non-adaptive controller with fixed gain cannot be allowed for this. But stable, excellent identification algorithm [Sripada and Fisher, 1987] for parameter is required to determine the suitable controller parameter in adaptive control. Mass is changed to 20 [Kg] at 1 [sec]. Airgap signal is given in Fig. 4.2.
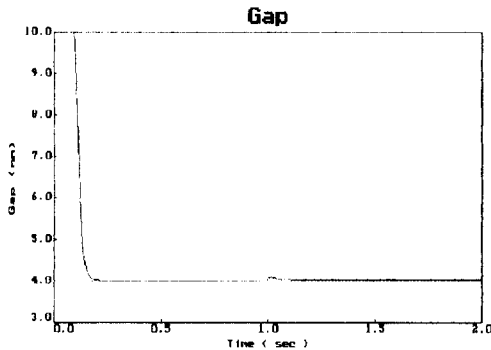

Fig. 4.2 Adaptive control when mass changes

As shown in Fig. 4.2, although there is mass variation, adaptive control gives no steady state error. In this case, the closed-loop poles are located at 0, 0.9, 0.91.

As a result of this simulation, adaptive control is superior to non-adaptive control when there is parameter variation. But to get better result, adequate initial parameters of L.S. algorithm are required. In this case, roughly the system parameters of linearized model at the equilibrium point are chosen.

In addition to initial parameter, sampling period too is important. Sampling period should be chosen with relation to system dynamics, i.e. time constant, relative order, etc. Covariance and forgetting factor of L.S. algorithm critically effect on the stability of L.S. algorithm when parameter varies abruptly.

The estimated parameters are shown in Fig. 4.3. Differently from linear model, it is very difficult to estimate the actual time-varying parameter. Since there are strong constraints in E.M.S. system, same input and output signal are obtained for some time. This makes the identification algorithm bursting. In this case, robust identification algorithm is necessary to avoid bursting.
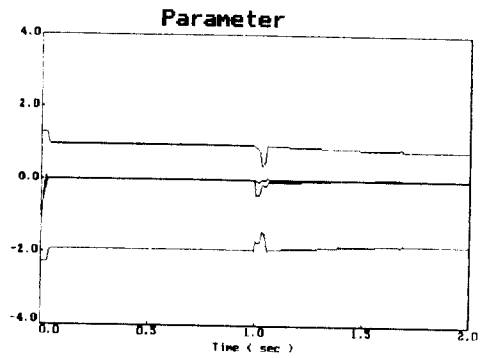

Fig. 4.3 Parameter estimation when mass changes

② airgap change

Reference airgap is changed to 4.5 [mm] at 1 [sec]. Airgap change effects on the variation of not only operating point in non-linear E.M.S. system but also plant parameters. It means that Differently from simple mass change, this case involves the non-linear problem as well as time-varying. As shown in Fig. 4.4, adaptive control presents worse transient response than state feedback control. The undesirable overshoot to opposite direction is the general phenomena that appear in the control of non-minimum phase system . Even though the system shows an overshoot, it converges to the desired value quite well. In this case, the closed-loop poles are located at 0, 0.9, 0.7.
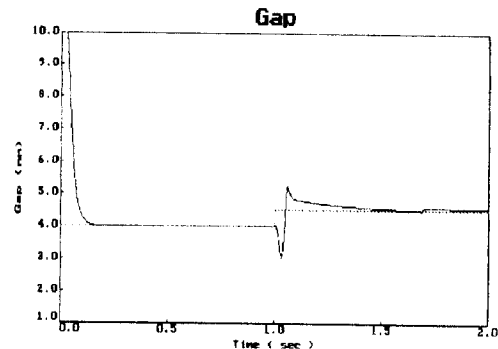

Fig. 4.3 Adaptive control when gap changes

4.3 Implementation strategy review

In this section, implementatation strategy of adaptive control algorithm of current source chopper drived E.M.S. system is simply shown. Least Square algorithm in section 4.1 requires about 97 times of multiplication algorithm and 54 times of addition. In diophantine equation and control law, matrix inverse operation takes so many times. It takes about 89 times of multiplication and 41 times of addition. TMS320C30 D.S.P. chip takes 200 [nsec] of multiplication and 60 [nsec] of addition.

Therefore the sampling period of more than 20 [KHz] is possible to process the adaptive algorithm. A D.S.P. board based adaptive control implementation is shown in Gurubasavaraj 's paper [1989]. Minimum Variance Controller using the first D.S.P. chip with fixed point operation in motor control is implemented. Hence it is possible to control E.M.S. system using the third D.S.P. chips with floating point operation.

5. Implementation example using D.S.P. board

Implementation example using D.S.P. board is shown in Fig. 5.1. As shown in Fig. 5.1, the voltage applied to the magnet is controlled by the control input u(t) via the D.C. chopper. This control input u(t) is determined by the control algorithm in D.S.P. board. The chopping frequency is 3 to 10 [KHz].
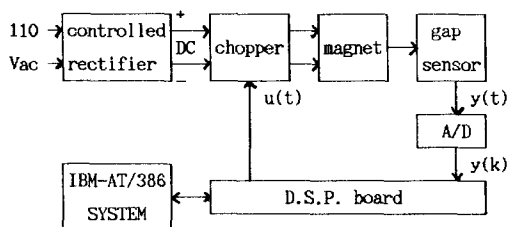

Fig. 5.1 H/W implementation example
of E.M.S. control system

6. Conclusion

In this paper, we have shown an adaptive control strategy for Electromagnetic Suspension System. Variation of mass and airgap urges the controller to be designed for non-linear and / or time-varying system.

As one of efficient solutions, adaptive pole-assignment control is considered. More robust identification algorithm and GPC are expected to improve the performance. For adaptive control of unstable system, initial start-up is another problem to be considered deeply.

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